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Extended Abstract+

Wave speeds in single-crystal and polycrystalline copper

Sarah A. Thomas[a],*, Robert S. Hixson[a], M. Cameron Hawkins[b], Oliver T. Strand[a]

[a]*Mission Support and Test Services, LLC, New Mexico Operations, Los Alamos, New Mexico 87544, USA*
bMission Support and Test Services, LLC, Nevada Operations, Las Vegas, Nevada 89030, USA

1. Introduction

While the equation of state for copper has been fairly well studied, wave speeds at low stress are not as well known. Systematic errors may be present in the lowest stress data presented in the Marsh [1] compendium due to the use of the flash gap method to collect the data. Additionally, little data has been gathered on the wave speeds in single-crystal copper, which may vary from polycrystalline due to the different longitudinal and shear sound speeds. Hugoniot information at low pressures is useful in constraining and improving predictive hydrodynamic codes. Knowledge of single-crystal behavior provides input for mesoscale computer models that use tens-of-micron-sized grains of single crystals to build a model of polycrystalline systems. We undertook experiments to measure wave speeds in polycrystalline and single-crystal copper at low pressures using a novel technique to limit error, and to determine if single-crystal shock velocities are systematically different than polycrystalline shock velocities at the same stress. The best previous research on this topic is from Chau et al. [2] at relatively high shock stress; they reported no observed difference between orientations. It is of interest to do careful measurements at low stress, and that is the principal goal of this work.

2. Experimental methods

A copper flyer plate impacted the base of a copper "top hat," with a larger diameter, thinner brim, and a smaller diameter, thicker top. The polycrystalline top hat was cut from a single piece of material. However, the single-crystal top hat was made from two crystals, the smaller-diameter piece glued to the center of the larger-diameter piece. We then used five channels of photonic Doppler velocimetry (PDV) [3], four around the brim, and one in the center of the top, to measure the free surface velocity at these points. Data from the four channels around the brim helped us determine the time that the elastic and plastic waves entered the base of the top part of the top hat. The center probe recorded the times the elastic and plastic waves exited the back of the top hat. The five channels of PDV allowed accurate cross timing.

Using timing data and thickness parameters of the top part of the top hat, we determined the speeds of the elastic and plastic waves. The wave profiles in Figure 1 show data taken from each of the five probes of a typical shot, with elastic and plastic waves labeled as E1 and P1, respectively. Having measured elastic wave speed, we compared it to the ultrasonically measured longitudinal sound speed (C_L) of the material and found it to be in fairly good agreement, lending credence to our subsequent shock speed measurements. We calculated the elastic wave speed by recording the time the elastic wave entered the center of the top section of the top hat (the same as the time the wave exited the back of the brim) and subtracted from it the time it exited the top, then divided the time difference by the top thickness. A similar calculation determined the plastic shock speed. Data were

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* Sarah Thomas. Tel.: +1-505-663-2068; fax: +1-505-663-2003.
E-mail address: thomassa@nv.doe.gov.

collected for polycrystalline and single-crystal [111], [100], and [110] copper at nominally 300 m/s. Two additional shots provided data on polycrystalline and single-crystal [110] copper at nominally 600 m/s.

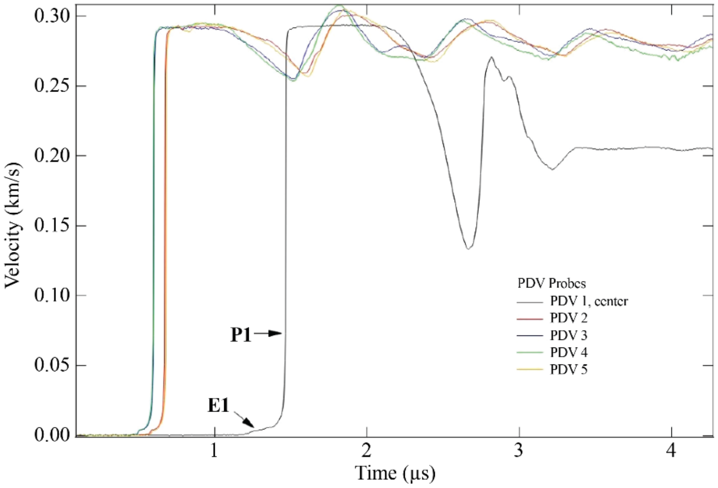

Fig. 1. Wave profile extracted from PDV data taken at the brim of the target.

3. Experimental results

Values for shock speed vs. particle speed are plotted in Figure 2 along with data taken from the Marsh [1] compendium. After careful error analysis, we believe the error in these data is about 2%, as concluded through a comparison of the elastic wave speeds with our ultrasonically measured ambient sound speeds. Note that one source of uncertainty is the perturbation caused by the elastic wave reflecting from the free surface as a small release and interacting with the oncoming plastic wave. We have quantified this effect in other work, and we find that in a material with a small elastic precursor such as copper, it is negligible with respect to other sources of error [4]. Figure 2 shows both the polycrystalline and single-crystal Hugoniot data plotted alongside archival data from Marsh. Taking an average of the shock velocities for each orientation of single-crystal as well as the polycrystalline velocities, we see that the differences between our results and the Marsh data is within around 2%.

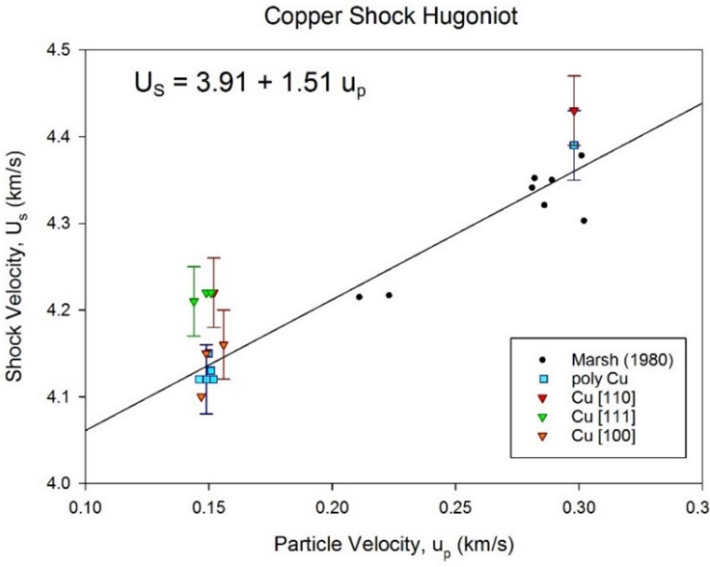

Fig. 2. Final results of shock Hugoniot of copper, including points from literature in black.

4. Conclusions

Careful measurements have been made of shock wave speeds in the three principal orientations of single-crystal and polycrystalline copper. Using a top hat target configuration, we observe differences in shock speeds between the different single-crystal orientations and polycrystalline copper, but those differences appear to be within the uncertainty from the experimental technique as determined from the elastic wave analysis. We stress that these are preliminary results, and believe that the technique is capable of making wave speed measurements with less uncertainty than we report here. Work will continue on analysis of this dataset. Extracting longitudinal sound speeds from copper wave profiles is difficult because the precursor wave is small and does not have a fast initial rise. We are working on a more comprehensive uncertainty analysis to better understand the inherent uncertainty budget. Because material anisotropy is an important technical question in the dynamic materials community, we will work to improve this technique.

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References

[1] Marsh, Stanley P., ed., 1980. LASL Shock Hugoniot Data, University of California Press, Berkeley, California.

[2] Chau, R., Stölken, J., Asoka-Kumar, P., Kumar, M., 2010. Shock Hugoniot of Single Crystal Copper, Journal of Applied Physics 107, p. 023506.

[3] Strand, O. T., Goosman, D. R., Martinez, C., Whitworth, T. L., Kuhlow, W. W., 2006. Compact system for high-speed velocimetry using heterodyne techniques, Review of Scientific Instruments 77, p. 083108.

[4] Thomas, S. A., Hawkins, M. C., Matthes, M. K., Gray III, G. T., Hixson, R. S., 2018. Dynamic Strength Properties and Alpha-Phase Shock Hugoniot of Iron and Steel, Journal of Applied Physics 123, p. 175902.